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The question of how a high-power RF pulse may affect a digital system such as a PC or an electronic control unit for a vehicle has become more important as sources of electromagnetic interference proliferate. The task of building a model for such an interaction is extremely challenging, requiring us to incorporate propagation and coupling of the electromagnetic fields, as well as circuit and system level effects. Rather than address this problem in its entirety, we choose to restrict our focus to a simpler system, specifically a microcontroller, and to RF waveforms directly injected into a set of signal lines. In this paper we will describe an integrated experimental and theoretical investigation of RF effects on n 8051-family microcontroller. We will describe our approach and present results from experimental investigations as well as a model for the probability of effect for an RF signal injected into signal lines carrying arbitrary logic pulse trains. Finally, we will describe how our results shed light on the broader problem of predicting the response of a general digital system to a high-power electromagnetic waveform.

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Modeling of Radio-Frequency Effects on a Microcontroller

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Abstract **– The question of how a high-power RF pulse may affect a digital system such as a PC or an electronic control unit for a vehicle has become more important as sources of electromagnetic interference proliferate. The task of building a model for such an interaction is extremely challenging, requiring us to incorporate propagation and coupling of the electromagnetic fields, as well as circuit and system level effects. Rather than address this problem in its entirety, we choose to restrict our focus to a simpler system, specifically a microcontroller, and to RF waveforms directly injected into a set of signal lines. In this paper we will describe an integrated experimental and theoretical investigation of RF effects on n 8051-family microcontroller. We will describe our approach and present results from experimental investigations as well as a model for the probability of effect for an RF signal injected into signal lines carrying arbitrary logic pulse trains. Finally, we will describe how our results shed light on the broader problem of predicting the response of a general digital system to a high-power electromagnetic waveform.**

1 INTRODUCTION

Building a model for the effect of a high-power RF waveform on a complex digital system such as a PC or an automotive electronic control unit presents a challenging problem. In addition to addressing the propagation and coupling aspects of the problem, it requires analysis of the electronic effects at the device, circuit and system levels.

Rather than tackle this problem in its full complexity, we have chosen to consider the electronic effects portion of the problem separately from the propagation and coupling piece. To gain insight into the behavior of a digital system we have chosen to investigate the case of an RF pulse injected directly into various lines of a microcontroller. A microcontroller is often described as a computer on a chip: as such it possesses the complex circuitry of a PC but without the additional complexity of a metallic case and multiple circuit boards, peripherals and connecting cables.

In section 2 we describe our general approach to investigating and modeling the effects induced on a microcontroller by an injected RF pulse. In section 3 we describe our experimental procedure, while we provide a summary of our theoretical approach in section 4. Finally, in section 5 we describe the results of two sets of experiments, and our conclusions.

2 APPROACH

Our approach is motivated by an earlier German study into the immunity of digital electronics to transient pulses ([1], [2]). This work investigated how a burst of 50ns electrical transient pulses affected a simple 8-bit 80C51 microcontroller, while it performed a single assembler instruction repeatedly. For this specific model of microcontroller, characteristic of early 8051 designs, a single assembler instruction is built up from 24 micro-instructions, associated with rising or falling edges of consecutive clock pulses. By controlling the timing of the incident pulses precisely to make them coincide with specific micro-instructions, they were able to develop an empirical susceptibility probability for each, and hence predict the susceptibility for the entire assembler instruction by aggregating these probabilities.

Our work adopts a similar approach, but in our case we are interested in exploring the effect of RF pulses on the microcontroller, rather than transient spikes. In addition, our objective is not simply to build an empirical model describing the probability of upset for specific instructions, but rather to develop a basic understanding of how an RF pulse interacts with the microcontroller to cause an upset. Our approach is to expose the microcontroller to RF pulses with carefully controlled onset times and durations, while making use of software implemented in assembly language to exercise various functional areas and hence various physical regions of the microcontroller, with the aim of developing fundamental insight into the upset mechanism.

Our ultimate goal is to build predictive models for the probability of upset as a function of the RF waveform parameters. In earlier work [3] we developed an initial probabilistic model to describe the effect of an RF signal injected into a clock line carrying a regular series of pulses on the operation of the microcontroller. In this paper we extend our theoretical approach to a more general model that describes the effect of an RF pulse on a signal line carrying an arbitrary pulse train.

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3 EXPERIMENTAL PROCEDURE

Our experimental approach was to mount the microcontroller on an evaluation board, both for ease of programming and to provide convenient connections for RF injection. We made use of an HP8116A pulse/function generator (figure 1) to generate an external clock signal for the microcontroller and to trigger a DG535 digital delay pulse generator. The pulse generator was configured to generate a specific number of square wave pulses, with a logic low at 0 volts and logic high at 5 volts, at a repetition frequency of 1 MHz.

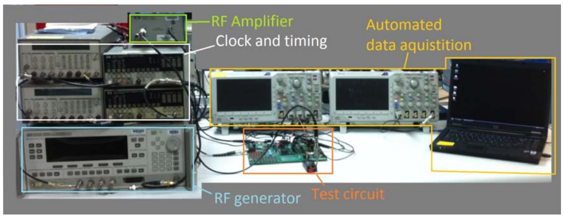

Figure 1: Experimental setup for microcontroller susceptibility investigation

The DG535 was used to trigger the oscilloscope for data collection, and to control the initiation time and duration of the RF pulse. The RF waveform itself was generated by an HP83620A Synthesized Sweeper as a CW signal with a frequency of 50 MHz and with a user-specified amplitude. The RF output signal was directly coupled into the microcontroller XTAL1 signal line, along with the external clock signal from the function generator. The microcontroller was programmed in assembly language to execute a simple binary counter, and we monitored the output of this counter to establish whether an upset had occurred.

For each suite of experiments, we performed the RF injection at a set of voltages ranging approximately from 0.5 to 5 volts, and recorded the response of the microcontroller. Specifically, we monitored the output of the counter, and documented whether or not the RF pulse resulted in an upset. At each voltage we repeated the experiment a specified number of times, and made use of a Bayesian approach to convert the binary data (effect/no effect) into a continuous probability of effect curve. We then summarized the curve for each location by the voltage associated with a 50% probability of upset (which we will refer to in the remainder of this paper as the threshold voltage), together with a 95% confidence interval (strictly a Bayesian credible interval).

4 THEORY

In developing a model to describe the effect of RF signals on a microcontroller we adopt a highly idealized view of the electronic system. We characterize the microcontroller as a machine with a number of functional pieces (e.g. control unit, ALU, registers) connected by multiple signal lines on which digital signals are transmitted back and forth. A number of external inputs (in particular a clock signal) are connected to the system via additional signal lines. Finally, we characterize the injected RF signals, which we assume to be square pulse modulated sinusoids, in terms of their carrier frequency, amplitude (voltage) and pulse duration, as well as their timing relative to clock or data pulses.

In previous work we considered the case of an RF pulse injected directly onto a clock line. In that case, we were concerned with a regular series of clock pulses. We constructed a simple model based on the assumption that the probability of effect was merely a function of the number of transitions (low to high or high to low) spanned by the interfering signal. In the current work we are concerned with the RF interaction with a general signal line carrying a signal pulse train (SPT) consisting of an arbitrary series of pulses. To analyze this case we have developed a more general model that describes the interaction of an RF pulse overlapping some portion of an SPT.

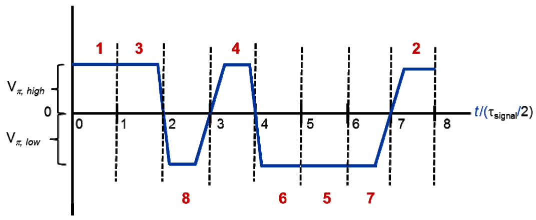

Figure 2: Eight elements necessary to construct an arbitrary signal pulse train

We note that any SPT can be characterized in terms of eight basic elements, shown in Figure 2, each with an associated probability of effect when encompassed by the RF pulse. This would suggest that there are 8^N or 2^{3N} possible ways in which these element could combined to produce an N-segment SPT. A more careful analysis, however, reveals that the requirement of continuity for the SPT imposes limitations on which of these elements can succeed a given element, and a quick inspection of the various cases reveals that any given element has two allowed successors. This constraint limits the total number of combinations for an N-segment SPT to 2^{N+2}.

We have developed a model for the probability of effect associated with an RF pulse that spans a section of the SPT, based on a number of assumptions. These include what we call modularity:

the assumption that the probability of effect associated with a single SPT segment is independent of its position in the full SPT. Based on this and other assumptions we can predict the probability associated with a partial segment, allowing us to compare experimental data we present below with the model predictions. In addition, we have developed a model to predict the effect on an unknown N-segment SPT, based on the probability distribution for the various possibilities. If we have some information about the tasks (software) running on the microcontroller we can bound this probability distribution, and hence bound the probability of upset associated with an injected RF pulse.

5 RESULTS AND CONCLUSIONS

The model we have developed suggests a number of experimental investigations. As a first step, we limited our study to a single instruction and the associated clock pulse, and investigated how the RF threshold voltage (the voltage associated with a 50% probability of effect) varies with two parameters: the onset time of the pulse relative to the clock pulse, and the pulse duration relative to a clock cycle.

Figure 3 shows the results for two different (nominally identical) microcontrollers as a function of onset time for RF pulses at frequencies of 25 and

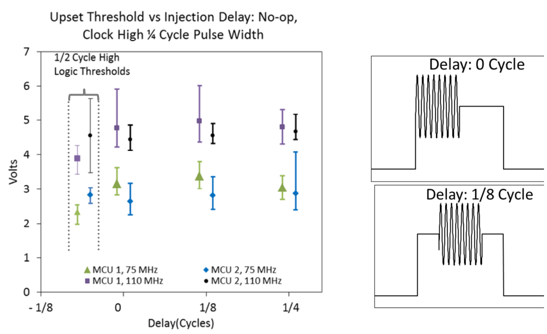

Figure 3: Upset threshold voltage variation with RF pulse delay relative to clock pulse

110 MHz, injected onto the clock line while a specific instruction (in this case a no-op instruction) is being executed. In this case an RF pulse with duration equal to a quarter of a clock cycle is injected during the logic high, with an onset time that varies between zero (the start of the high) and 1/4 clock cycle (the RF pulse finishes at the end of the logic high). In each case we have repeated the experiment for two (nominally identical) microcontrollers, and the results are generally in good agreement.

Figure 4 shows our results for a 110 MHz pulse with durations varying between 1/16 and 1/2 of the clock period. In this case, each pulse is centered on the mid-point of the logic high. As we would expect, the threshold voltage decreases as the pulse duration increases.

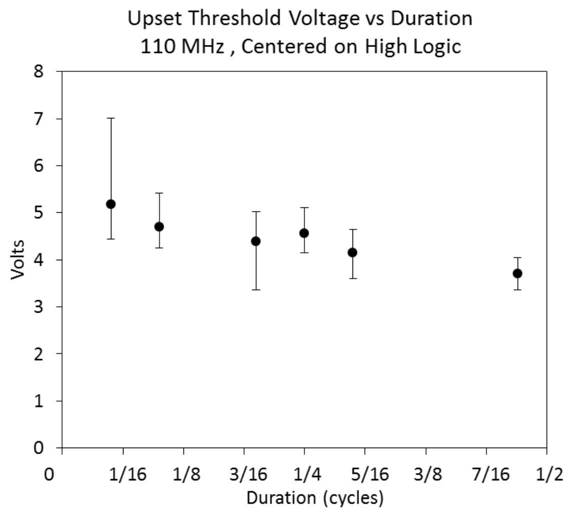

Figure 4: Upset threshold voltage variation with RF pulse duration relative to clock pulse

The results we have shown are generally consistent with what our model would predict, but they represent a very limited set of data. To fully explore the nature of the response of the microcontroller to an injected RF pulse will require a much more extensive experimental effort.

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